CHAPTER 7
THE LIFE OF STARS BEYOND THE MAIN SEQUENCE

7.1 Introduction

The distribution of stars on the Hertzsprung–Russell diagram tells us that the majority of them lie on the main sequence. Stellar models (Chapter 6) tell us that their stability is a result of the balance between the inward force of gravity and the outward force of gas pressure (and for higher mass stars, radiation pressure). The outward pressure is sustained by the energy provided from fusion of hydrogen to helium. The rate of energy production, and hence the lifetime of the star on the main sequence is highly dependent on the temperature and hence the mass of the star.

- What determines the end of a star's lifetime on the main sequence?
- The end of the main sequence lifetime is marked by the exhaustion of hydrogen in the core.

What happens to a star when this occurs? The position on the H–R diagram of a star undergoing hydrogen burning is determined by its mass and composition. When the process that maintains the star's structure no longer operates, the structure of the star and hence its temperature and luminosity will change. It will therefore move to a new location on the H–R diagram. Even before such drastic changes occur the star will still move slightly on the H–R diagram since its composition is continually changing as hydrogen is being converted into helium in the core. The main sequence therefore has a finite width on the H–R diagram with stars of the same mass but different ages and hence different compositions being in slightly different locations.

In this chapter we will look at the changes that occur in stars of different masses after the supply of hydrogen in their cores has been exhausted. In particular, we will examine the changes in structure and the changes to energy sources that occur after the main sequence life of stars.

7.2 Post main sequence lifetime of low-mass stars

7.2.1 Hydrogen shell burning

Generally, it is only in the core that it is hot enough for fusion reactions to occur. So the question arises – does the core get replenished with hydrogen through convective mixing between the core and the rest of the star? Convection in the core region occurs only in the more massive stars, but even there, as Figures 6.4 and 6.5 show, it does not extend much beyond the core. The rate at which hydrogen is depleted in the core is thus determined by the rate at which nuclear reactions take place there, and a critical point will be reached when the hydrogen has all gone. Once this stage has been reached, nuclear reactions in the core will stop. The core will then start to contract (slowly) as it is no longer releasing energy at a sufficient rate to generate a pressure gradient sufficient to support the surrounding layers. As a result of this contraction, gravitational energy is converted into thermal energy and

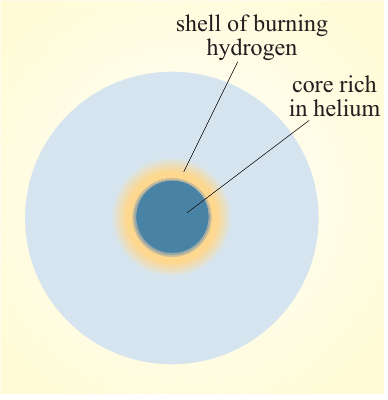

Figure 7.1 Schematic drawing of a star with a shell of burning hydrogen.

the temperature will rise. This means that a shell of unprocessed material surrounding the original core will be heated sufficiently for hydrogen burning to start. This is illustrated in Figure 7.1.

7.2.2 Helium burning

While the hydrogen shell burning occurs the core continues to contract and, in doing so, continues to heat up as more gravitational energy is converted into thermal energy. When a temperature of around 10^8 K is reached, a new range of nuclear reactions becomes possible.

- Bearing in mind what you know of the composition of the core at this stage and what you learned from Box 6.1, what do you think may be the next set of nuclear reactions?
- The core now consists predominantly of helium, and from Box 6.1, we suspect that **helium fusion** reactions should now occur – these would be exothermic (Figure 6.6).

We might expect therefore that two helium nuclei would combine in some way to produce ${}^{8}_{4}\mathrm{Be}$. However, ${}^{8}_{4}\mathrm{Be}$ is very unstable and almost immediately decays back to two helium nuclei. So is there any way in which helium burning can take place and nuclear reactions continue? It was not until the 1950s that the full details were worked out. It was appreciated that, at the temperature and density likely to prevail in the helium core of a post main sequence star, it would occasionally happen that the short-lived beryllium nucleus would meet another helium nucleus before it decayed. The result is the formation of a ${}^{12}_{6}\mathrm{C}$ nucleus. The overall scheme is therefore:

The $\rightleftharpoons$ symbol emphasizes the fact that this is a two-way reaction.

$$
{}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightleftharpoons {}^{8}_{4}\mathrm{Be}
$$

$$
{}^{8}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{12}_{6}\mathrm{C} + 2\gamma
$$

This chain is known as the **3α (triple alpha) process**, α being the commonly used symbol for the helium nucleus, because the net effect is the conversion of three helium nuclei into a ${}^{12}_{6}\mathrm{C}$ nucleus. The onset of the 3α process – helium burning – halts the contraction of the core and stabilizes the star.

Helium burning is initiated at temperatures of around 10^8 K and furthermore is remarkably sensitive to temperature: the rate of energy release by this process is proportional to the 40th power of temperature! This sensitivity arises because the third α-particle needs to fuse with the beryllium nucleus to form the carbon nucleus before the beryllium decays back to two helium nuclei. At high temperatures the nuclei are moving at high speeds and therefore there is a greater probability of interaction.

The 3α process releases 1.17×10^{-12} J of energy per ${}^{12}_{6}\mathrm{C}$ nucleus, or 3.9×10^{-13} J per ${}^{4}_{2}\mathrm{He}$ nucleus. This latter figure is only about 10% of the energy released in forming the helium nucleus from hydrogen. This fact, coupled with the higher luminosity during this phase, ensures that the time until the helium in the core is exhausted, which we take to define the end of this phase, will be considerably shorter than the main sequence lifetime. As a rough rule of thumb, the length of the helium-burning phase is about 10% of the main sequence lifetime.

7.2.3 The giant phase

What has been happening to the rest of the star during this post main sequence phase? The contraction of the core, which was initially slow, has speeded up under the pressure of the outer regions of the star. Simultaneously, however, the radius of the star as a whole *increases*. Although this surface expansion which accompanies the core contraction is predicted by the equations of stellar structure, the explanation is not straightforward. It is also predicted that this expansion is not accompanied initially by a significant change in luminosity.

QUESTION 7.1

What will happen to the temperature of the outer layers of the star at this phase, bearing in mind the comment above about the star's luminosity in this immediate post main sequence phase?

As hydrogen burning in the shell around the core progresses, the luminosity is expected eventually to increase as convection carries energy to the surface. As an example, for a star of $1M_{\odot}$, the core will be compressed to about 1/50th of its original size and the core temperature will rise from 15×10^6 K to about 100×10^6 K. At the same time, the diameter of the star will increase by about a factor of 10, with a surface temperature falling to about 3500 K. This causes the star to glow with an orange-red hue, and this, together with its size, gives it its name: red giant. Once the core temperature has risen sufficiently, helium starts to burn in the core and the star now enters the next phase of its red giant life.

What about the paths of these stars on the H–R diagram? These are shown in Figure 7.2 for stars of different masses. Notice that as the red giant phase is approached, the tracks tend to crowd together. This indicates a fairly narrow range of conditions for red giants.

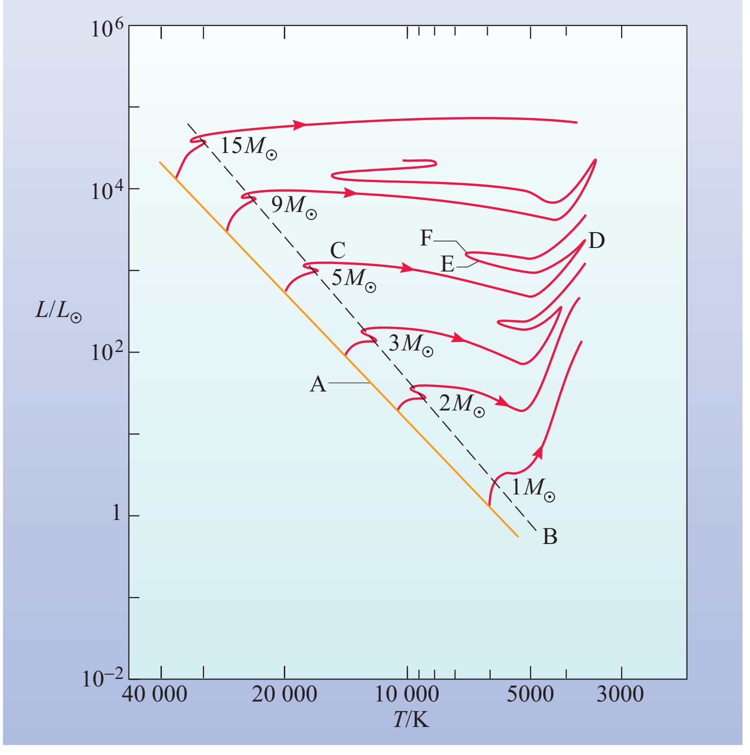

Figure 7.2 The predicted paths of stars on the H–R diagram as they evolve off the main sequence to the red giant (or supergiant) phase. The letters on the $5M_{\odot}$ track refer to different stages of nuclear reactions in the star. The line marked A denotes the onset of hydrogen core fusion – the start of main sequence life. The dashed line B denotes the cessation of hydrogen core fusion – the end of main sequence life, and the onset of hydrogen shell fusion. Subsequent stages are labelled on the $5M_{\odot}$ track only: (C) hydrogen shell fusion continues; (D) helium core fusion starts; (E) helium core fusion continues; (F) helium shell fusion starts. The small loops to the left for the $1M_{\odot}$ and $2M_{\odot}$ stars have been omitted for clarity.

After helium fusion starts in the core, the tracks retreat from a peak value of luminosity and migrate backwards and forwards on the H–R diagram (the extent of migration depends on the mass) as the red giant readjusts to its new sources of energy. Figure 7.2 also shows that post main sequence stars of mass greater than ~$2M_{\odot}$ are not always at temperatures that give them an orange hue – they can be far hotter than this. Such stars, with luminosities comparable with those of red giants, plus the red giants themselves, are the *giant* stars introduced in Section 4.2.2.

Stars lying on the H–R diagram between the main sequence and the giants (i.e. to the right of the line labelled B in Figure 7.2) are, unsurprisingly, called **subgiants**. In evolutionary terms, subgiants consist of stars en route to becoming red giants.

Figure 7.3 illustrates the evolutionary track of a $1M_{\odot}$ star indicating key regions on the H–R diagram. After leaving the main sequence the star ascends the **red giant branch** (often abbreviated to RGB) with energy production from hydrogen shell burning. (Note from Figure 7.2 that stars of a wide range of masses reach this zone of the H–R diagram at the same stage of their evolution.) After the helium flash (explained in Section 7.2.4 below) the star undergoes helium core burning and moves approximately horizontally (i.e. with relatively constant luminosity) to higher temperatures. This places the star in a region of the H–R diagram called the **horizontal branch** (HB). Once core helium burning ceases, the star once again cools, but expands and increases in luminosity, approaching the red giant branch from the left. This region is called the **asymptotic giant branch** (AGB). Figure 7.3b shows an H–R diagram for a globular cluster (an old cluster which therefore contains many evolved low-mass stars; Sections 3.2.4 and 4.2.5) which illustrates

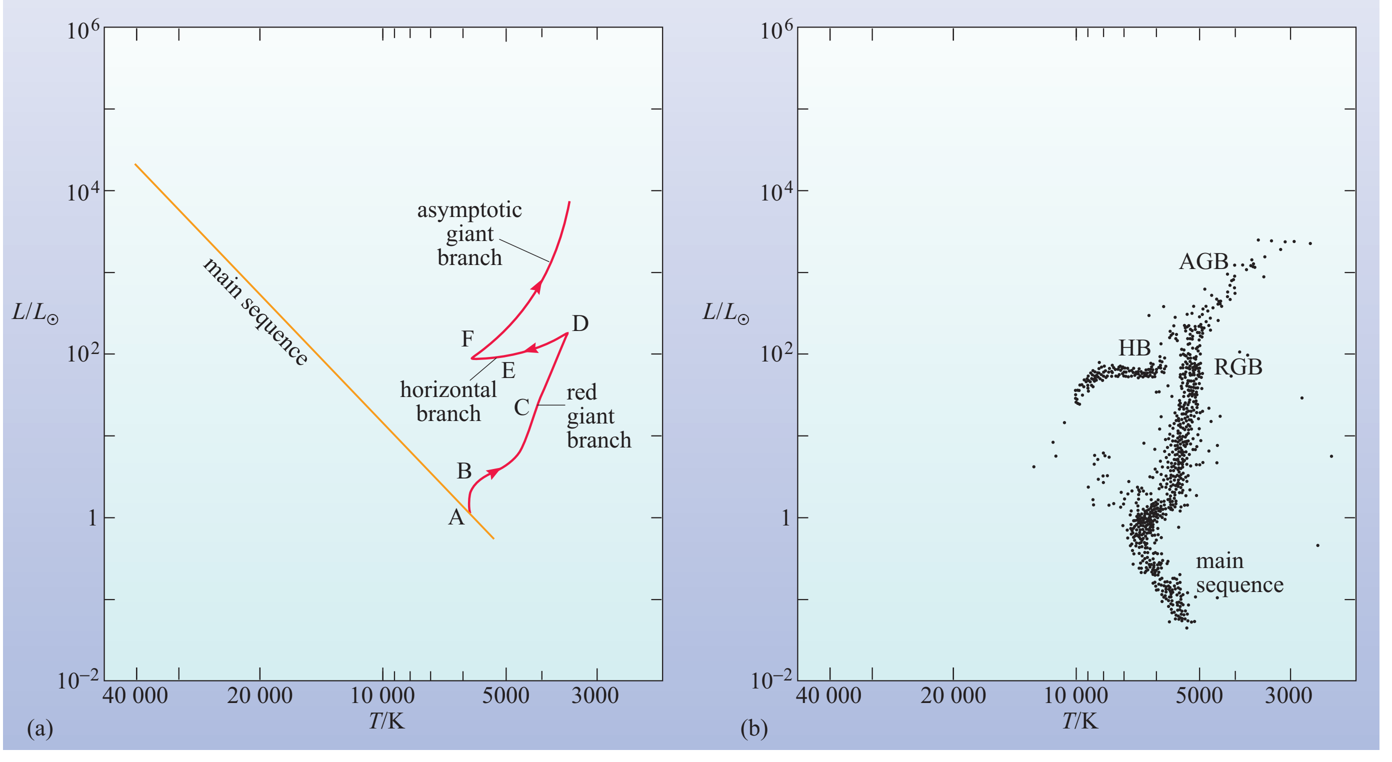

Figure 7.3 (a) The predicted path of a $1M_{\odot}$ star, plotted on the same scale with the same labels as Figure 7.2, (A) hydrogen core fusion; (B) onset of hydrogen shell fusion; (C) hydrogen shell fusion continues; (D) helium core fusion starts; (E) helium core fusion continues; (F) helium shell fusion starts. (b) The H–R diagram of a globular cluster which illustrates how stars tend to concentrate in these regions.

the tendency for stars to concentrate in these regions. For example stars of different masses all cluster in a horizontal bar, the horizontal branch, during helium core burning. (Note that the main sequence is not in quite the same place as in Figure 7.3a due to the fact that the chemical composition of the interstellar material was somewhat different at the time these stars formed. This will be discussed further in Section 8.4.3.)

We will now look in more detail at what happens within the star during these stages of its evolution.

7.2.4 The helium flash

The manner in which the helium burning starts depends on the *mass* of the star, with an important difference between stars with masses below and above about $2.25M_{\odot}$.

At the root of this difference is a phenomenon known as **degeneracy**. A detailed description of degeneracy is beyond the scope of this book – it requires a knowledge of quantum mechanics. However, we do need to know something about this phenomenon in order to understand several features of the evolution of stars after they leave the main sequence. Up to now we have been able to assume that the gas inside a star behaves like an ideal gas. For such a gas, simple equations, such as Equation 6.1, can be used to describe the relationships between pressure, temperature and density for example. At the extreme densities that exist deep inside some stars, the matter may be so compressed that a different set of equations must be used to describe the physical properties of the *electrons* in the gas – remember that the atoms are ionized, so we have an electron gas mixed up with a gas of atomic nuclei. This is the so-called degenerate electron gas. It has various properties that differentiate it quite clearly from the more normal gases that we are familiar with.

We shall focus on one property in particular and see how this affects the behaviour of red giants of low mass. Equation 6.1 shows that, if the temperature of an ideal gas is increased, its pressure will increase proportionally if other properties remain unchanged. The increase in pressure leads to expansion, and hence to cooling. For a degenerate gas, however, the situation is different. When the temperature changes, the pressure is unaffected. The pressure (called **electron degeneracy pressure** for a degenerate electron gas) depends on density and composition rather than temperature.

Why is this relevant to the situation we find in red giants? If helium burning starts in an ideal gas, this is basically a stable process. If a small temperature rise occurs in the helium-burning core we can expect an increased rate of release of energy because the nuclear reaction rate depends on a high power of the temperature. If the stellar material is fairly opaque, the energy may not be able to escape. Therefore, the local temperature will rise – in an ideal gas, this will result in the pressure rising, the gas expanding and cooling, and therefore the rate of nuclear reactions falling. There is, in other words, an in-built stability to the whole process.

However, if helium burning starts in a degenerate gas, the situation can be very different. Because the pressure in a degenerate gas is now nearly independent of temperature, the rise in temperature on initiation of nuclear processes does not produce a consequent rise in pressure, expansion and cooling to control the initial rise in temperature. This rise in temperature therefore causes the helium burning to continue even faster. In addition, degenerate material is a very good conductor of heat so once the temperature is high enough for helium fusion to start in one part of

the core, the turn-on spreads throughout the core very rapidly. This is an unstable situation – the process can start to 'run away' and produce an explosive release of energy in the degenerate core of these lower mass stars. This is usually termed the (core) **helium flash**. This is, incidentally, believed to be one of the few cases in the history of a star where an event occurs over a timescale perhaps as short as a matter of hours or less. However, although the helium flash happens very quickly in the core, the release of energy takes very much longer to reach the surface.

One result of the helium flash is to raise the core temperature to the point where the degenerate conditions are removed (see Figure 7.4). Once degeneracy is removed in this way, then the core can expand and cool and the situation will be stabilized.

Under exactly what conditions does degeneracy occur? Figure 7.4 shows a plot of density against temperature divided into two regions corresponding to normal (i.e. non-degenerate) and degenerate conditions. The transition between the two is not sharp and so is indicated by a fuzzy boundary. The region occupied by the cores of main sequence (i.e. hydrogen burning) stars is indicated. Stars of lower mass, after their main sequence lifetime, evolve into the region corresponding to degenerate conditions, whereas higher mass stars achieve core temperatures at which helium burning is initiated before degenerate conditions are reached.

To summarize, the evolution of stars after they leave the main sequence depends on whether degeneracy sets in before helium burning (the 3α process) is initiated. If the mass is greater than about $2.25M_\odot$, the helium reactions start before the core can become degenerate. For stars with masses less than about $2.25M_\odot$, helium burning starts in a degenerate core in a violent reaction known as a helium flash. This will probably remove the degenerate state of the core.

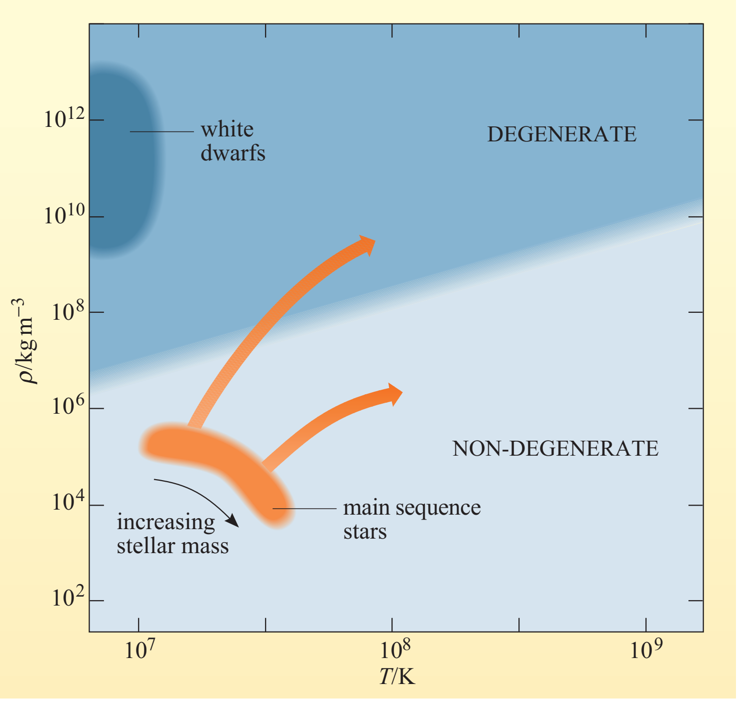

Figure 7.4 Conditions for degeneracy in an electron gas. The conditions in the cores of main sequence stars are shown together with arrows indicating the change in core temperature and pressure as they evolve up to the point of onset of helium burning. White dwarfs are discussed in Section 9.2.

7.2.5 Internal structure

The changes in the structure of a star during the post main sequence phase are quite complicated. Figure 7.5 shows what happens in a star of $5M_\odot$ after it leaves the main sequence. The different processes that occur at the various zones in the cross-section of the star are indicated in the lower panel by the different coloured regions. The horizontal axis indicates the time since the start of the star's life on the main sequence (i.e. since hydrogen burning commenced). The quantity plotted on the vertical axis is the mass fraction, M_R (the fraction of the total mass inside a given radius as we move outwards from the centre of the star). $M_R = 0$ at the centre of the star and $M_R = 1$ at the surface of the star. This quantity is used rather than the radius because the nuclear reactions are taking place in a region that is very small and yet contains an appreciable proportion of the star's total mass. Also, the radius of a star changes enormously as the star evolves but the total mass remains constant (at least until the later stages of evolution – see Chapter 8). The compact nature of the helium-burning inner core is clear from Figure 7.5. It is also clear that (a) hydrogen burning will continue in a thin shell, which will be at the surface of the helium zone, though well away from the helium-burning inner core, and (b) after depletion of helium in the core, helium burning will continue in a shell that moves progressively outwards as further helium is used up. These factors are partly responsible for the tortuous path predicted for some stars across the H–R diagram during the giant phase (Figure 7.2).

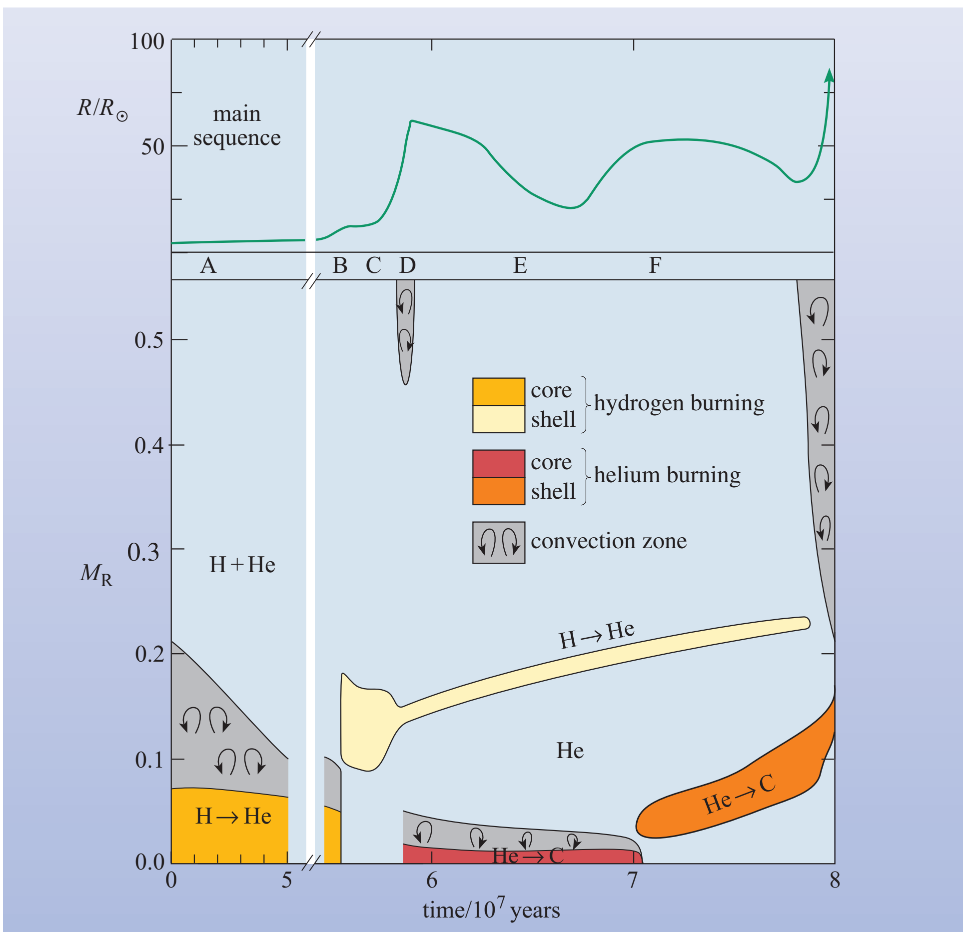

Figure 7.5 Schematic representation of the internal structure of a star of mass $5M_\odot$ during and after its main sequence lifetime. The upper panel shows the change in radius of the star with time. Note there is a change of scale in the time axis between 5 and 6×10^7 years to reflect the faster evolution of the star after it leaves the main sequence. The lower panel shows the change in composition and nuclear reactions in the star as it evolves. The vertical axis is the mass fraction M_R (the fraction of the total mass inside a given radius as we move outwards from the centre of the star), with the centre of the star at the bottom. The coloured regions indicate the locations of nucleosynthesis and the grey zones are convection zones. The labels A to F indicate the times of significant changes in the nuclear reactions as shown on the evolutionary track on the H–R diagram in Figure 7.2.

7.2.6 Pulsating variables

Giants that have evolved to the stage at which core helium burning has started are often intrinsic variables. One class of intrinsically variable star – the Cepheids – was introduced in Section 3.3.5. The variability in Cepheids and related stars results from a large amplitude pulsation of the star – in which the radius of the star periodically varies with an amplitude which may exceed ten per cent. Although this is a much larger effect than the five-minute oscillations of the Sun that you met in Section 2.2, the way in which these pulsations propagate through the star is similar. The principal difference between the two effects arises from the mechanism that drives the pulsations.

- ■ What is the mechanism that drives small-scale global oscillations of the Sun?
- ❑ Convective motions are the likely source of disturbance that drives global solar oscillations (Section 2.2.6)

The much larger pulsations that are observed in Cepheids arise from an instability in the envelope of the star. The way in which this instability gives rise to oscillations can be appreciated by considering a thin (spherical) layer of gas within the envelope of the star. Compressing this layer results in an increase in temperature and this gives rise to an increase in opacity (a measure of the absorption of radiation). The rate at which energy is transported by radiation through the layer is thus reduced, and this results in heat being trapped below the layer. Thus the temperature and pressure below the layer increase, and the increase in pressure drives the layer outwards. The layer now expands, its density drops and it becomes more transparent hence allowing heat to pass out through the layer. The pressure below the layer then drops and so the layer falls and becomes compressed. This cycle then repeats itself. The underlying physical cause is the change in opacity with temperature, and this comes about because of the ionization of He^{+} to He^{2+}. This ionization increases the density of free electrons, and because electrons interact strongly with radiation, the result is a drop in transparency. This condition arises at a certain temperature (about 40 000 K), and so the layer that exhibits this instability exists at a particular radius within the star.

In order for the star to show large-scale pulsations, it is necessary that the location of the unstable layer is at a position that can drive the oscillation. This behaviour is somewhat similar to the behaviour of the type of swing that is commonly found in children's playgrounds. You may know from experience that in order to achieve a large amplitude oscillation in a swing, you have to provide a push at the correct moment – at the time when the swing has momentarily stopped and is at its maximum height above the ground. If you try applying a push at other parts of the cycle, then the oscillation does not build up to large amplitudes. By analogy, in a Cepheid, the unstable layer is in just the correct part of the star to provide regular 'pushes' that give a large amplitude global oscillation of the star. If the layer is too near the surface or too close to the core, the motion of the unstable layer does not match itself to the global oscillation of the star and pulsation does not occur.

Because the phenomenon of large amplitude pulsation requires a particular combination of conditions in the envelope of the star, we shouldn't be surprised to learn that these stars appear to occupy certain well-defined positions on the H–R diagram. The pulsating classes of stars include Cepheids and RR Lyrae stars, as well as lower luminosity examples such as the so-called delta Scuti stars. The region on the H–R diagram in which the pulsating stars lie is termed the **instability strip**, which extends from the supergiant region to below the main sequence as shown in Figure 7.6.

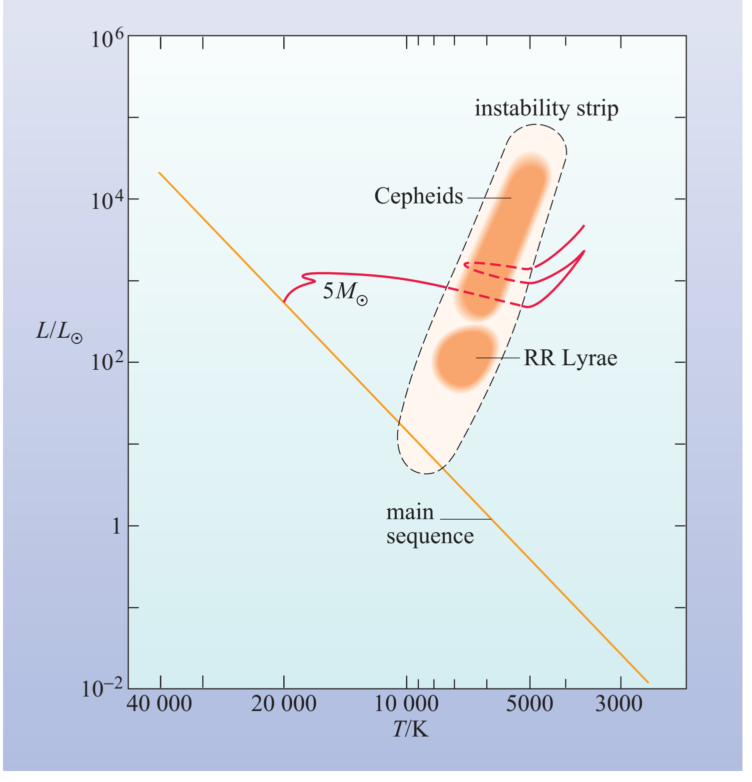

Figure 7.6 The position of the instability strip on the H–R diagram. The evolutionary track of a $5M_\odot$ star is shown dashed where it is exhibiting pulsations. At this time its position on the diagram will oscillate due to its changes in temperature and luminosity.

During the course of their evolution, many stars will pass through this region and thus display this type of instability. Comparison of Figures 7.2 and 7.6 shows that, in the post main sequence phase, the part of the instability strip that will be crossed depends on a star's mass, and thus stars of different mass might be expected to fall into different pulsating classes. The Cepheids correspond to stars of mass greater than about $2M_\odot$; these are giants and supergiants that cross the instability strip as their evolutionary tracks loop across the H–R diagram.

The RR Lyrae stars are those that lie at the intersection of the instability strip with the horizontal branch, and hence correspond to stars with a mass of between $0.7M_\odot$ and $2M_\odot$. RR Lyrae stars all have periods of less than one day and have roughly the same luminosity of around $100L_\odot$. These stars are found in globular clusters (Section 3.2.4) and are used to determine distances to such clusters in much the same way as Cepheids are used to determine distances (Section 3.3.5).

Although there is also an intersection of the instability strip with the main sequence, the numbers of such stars that have been identified is relatively low because the variation in luminosity is small and consequently these stars are hard to detect. Also, as shown in Figure 7.6, a star can pulsate when it crosses the instability strip for the first time during hydrogen shell burning. However, this phase is much shorter than the helium core burning phase normally associated with Cepheid variables. However, across the entire luminosity range of the instability strip, many thousand stars are known to be variables of the pulsating envelope type, so they clearly are relatively common.

The study of variable stars is a very important tool that enables astronomers to probe the structure of stars, and can potentially yield more information than observations of non-varying stars. The time a star spends on the instability strip is thought to be not particularly long, and ends once the conditions that are necessary for pulsation are removed by the continued evolution of the star.

QUESTION 7.2

Which of the stars listed in Table 7.1 could be pulsating variables on the basis of their position on the H–R diagram shown in Figure 7.6?

Table 7.1 Data for Question 7.2.

Star	Spectral type	M_V
X	F0	3
Y	K5	–6
Z	A0	1

7.2.7 Very low mass stars

For stars of mass less than about $0.5M_\odot$, we find a very different story. Theoretical calculations show that the critical mass below which helium burning is unlikely to start is around $0.5M_\odot$. The evolutionary track of a star with a mass somewhere between $0.1M_\odot$ and $0.5M_\odot$ is shown in Figure 7.7. Initially, the star evolves in a similar direction (compare with Figure 7.2) to a star of slightly higher mass. However, helium burning never starts in such a star, so the luminosity soon peaks and then declines rapidly.

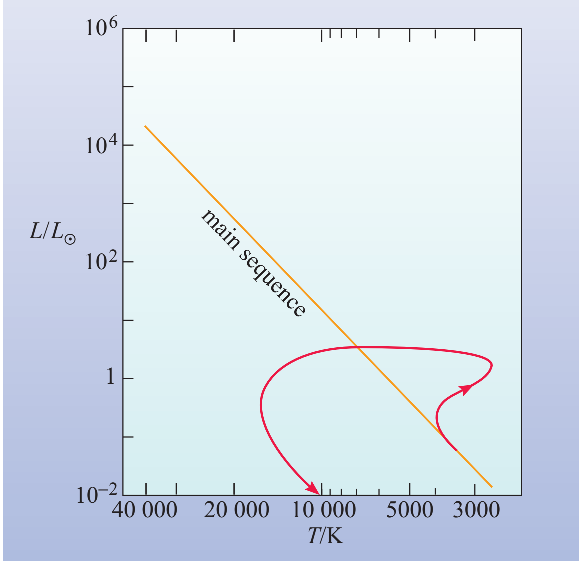

Figure 7.7 The post main sequence evolutionary track of a star of mass between approximately $0.1M_\odot$ and $0.5M_\odot$.

7.2.8 Further reactions in giants

Is there anything more that can happen to a star in the giant phase? In addition to the helium-burning reactions, there is another reaction that occurs in all giants. The $^{12}_{6}C$ nuclei produced by helium burning can capture an additional α-particle in the following reaction

$$^{12}_{6}C + ^{4}_{2}He \rightarrow ^{16}_{8}O + \gamma$$

to produce the heavier nucleus, $^{16}_{8}O$. This reaction and the 3α process in red giants are thought to be the main sources of oxygen and carbon in the Universe. (Note that this reaction producing oxygen from carbon should not be confused with the CNO cycle in which carbon, nitrogen and oxygen are involved in the process of conversion of hydrogen into helium in massive stars as described in Section 6.3.)

The addition of another α-particle results in the production of neon:

$$^{16}_{8}O + ^{4}_{2}He \rightarrow ^{20}_{10}Ne + \gamma$$

although this is only a minor reaction in stars of this mass.

Giants with a mass less than about $8M_{\odot}$ do not develop core temperatures high enough to trigger any further nuclear reactions beyond that which produces oxygen. The cores of such stars accumulate carbon and oxygen, the remnants of helium burning. When the helium in the core is exhausted, the core begins to contract again. This heats the helium surrounding the core sufficiently to trigger helium burning, the 3α process, in a shell. This situation is shown schematically in Figures 7.5 and 7.8. The star is now on the asymptotic giant branch (AGB).

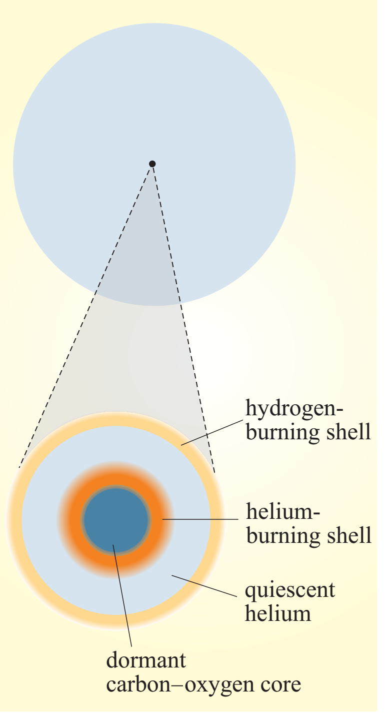

Figure 7.8 The structure of an old red giant of low mass ($<4M_{\odot}$). The star has a size comparable with the orbit of Mars.

Shell helium burning has caused the giant to expand further and move upward on the H–R diagram for the second time. The star is now even larger – its size can be as large as the orbit of Mars! However, this situation isn't stable. The helium-burning shell is rather thin and this causes a thermal runaway to occur. The result is another helium flash, but quite different from the core helium flash that you have already met. In that case, the cause was degeneracy but now, in the helium-burning shell, the material is not compressed enough for degenerate conditions to be reached. These **shell helium flashes** are due to the fact that the shell is too insubstantial to lift the material above it. Thus, as shell helium burning gets underway, the shell cannot expand and so the temperature rise is not moderated. The helium burning rate increases, increasing the temperature further. This leads to a rapid release of energy, sometimes called a **thermal pulse**, which lasts a few hundred years. These flashes are thought to be approximately periodic events but separated by intervals of 10^4 to 10^5 years. During the thermal pulse, conditions in the helium-burning shell are right for another type of nuclear reaction to take place in parallel; this is called the **s-process reaction** (where s is for slow; you will meet the r or rapid process in Section 8.3.1).

In the s-process a neutron is added to an existing nucleus to make a heavier one.

- Why should neutrons be able to react easily with a nucleus?
- They are neutral particles, so there will be no electrostatic repulsion as would be the case if they possessed a positive charge. Thus reactions can take place at low temperatures.

In the s-process nuclei capture neutrons slowly in the sense that for any nucleus, the typical time between neutron capture reactions is very long. The reason for this is that the density of free neutrons is relatively low. If this addition results in an unstable nucleus there is time for some radioactive decay (usually by the emission of an electron) before the next neutron capture takes place. By the slow, steady addition of neutrons, interleaved with some radioactive decay, nuclei as heavy as $^{209}_{83}\mathrm{Bi}$ are created. Some isotopes such as $^{80}_{36}\mathrm{Kr}$ and $^{82}_{36}\mathrm{Kr}$ can only be created through the s-process.

The thermal pulse has other effects as well, which help us see what is happening in the inner parts of the star. The release of energy in the helium-burning shell alters the pattern of convection in the star, so that a deep convective envelope is formed. Convection reaches right down from the surface to the helium-burning shell, and circulates surface material down to that level while dredging some of the helium burning and s-process products up to the surface (you can see that a deep convective envelope appears at the extreme right-hand edge of Figure 7.5). Spectral lines from these elements can then be seen in the star's spectrum. Due to the s-process plus the 'dredge-up' by convection, the radioactive element technetium

has been seen in the spectra of some stars. Technetium is an unstable element which decays typically in a few million years. If the surface of the star was not refreshed from below then radioactive elements like technetium would have decayed long ago and would no longer be seen in the star's spectrum. If the s-process were not currently taking place in the interior of the star there would be no technetium to bring to the surface. Short lifetime (on an astronomical timescale) elements on the surface of a star, far from the regions where nuclear reactions take place, testify to the large-scale circulation of material in the star. The actual elements found tell us which nuclear processes are taking place inside the star.

The thermal pulses may play a part in the ejection of large amounts of material, a phenomenon observed to take place towards the end of the lives of some stars (as you will see in Chapter 8).

The various processes that have been discussed in the giant phase explain why the evolutionary track on the H–R diagram at this time is predicted to be quite complicated (Figure 7.2). Every time a new energy source dominates the star's evolution, the direction on the H–R diagram is likely to change. We should remember, however, that this part of a star's lifetime is short compared with the main sequence lifetime – for a $1M_{\odot}$ star, 10^9 years as opposed to 10^{10} years. This is why we would expect to observe far fewer stars in the giant stages of their evolution compared with those on the main sequence.

In the final stages of their lives, low-mass stars become variable stars and undergo mass loss culminating in the loss of their outer envelopes and formation of dense stellar remnants called white dwarfs. This final stage of their evolution will be discussed in Chapters 8 and 9.

7.2.9 Winds from red giants

Before we finish discussing the main phase of the life of a giant, we should consider one important effect of its increased radius. The star's gravity at its surface will be very much less than what it was during its main sequence lifetime since the mass has not changed significantly but the radius has increased considerably. This means that atoms in the red giant's atmosphere can more easily escape, resulting in a copious stellar wind, though at a lower velocity than that of the main sequence stellar wind. Mass loss rates of up to $10^{-6}M_{\odot}$ per year are possible for the most luminous red giants. Winds from red giants can therefore be responsible for a more significant loss of the star's total mass, in contrast to the very small loss by this mechanism during the main sequence lifetime. Mass loss in highly evolved stars will be discussed in more detail in Chapter 8.

7.3 Post main sequence lifetime of high-mass stars

We have seen that stars like the Sun, and those of up to a few times the mass of the Sun, when they run short of hydrogen in their cores, swell to become red giants and undergo helium fusion. What is the fate of stars much more massive than the Sun?

You saw in Section 6.2.5 that massive stars have a much shorter lifetime on the main sequence than lighter stars. Because they are more massive they have a higher central temperature, and so the hydrogen-burning nuclear reactions proceed faster. Because their nuclear reactions proceed faster, energy is released more quickly and so these stars are also brighter. For a short while they are hot and bright, and are found in the top left-hand part of the H–R diagram (spectral types O and B).

Some stars (those that formed relatively recently) are still to be found in that part of the H–R diagram. But where are those that formed earlier? Stars that were once on the main sequence in the top left-hand corner of the H–R diagram are today's **supergiants**. (See Figure 4.5 to remind yourself where the supergiants are located in the H–R diagram.)

You have already met two of the prominent stars in the constellation of Orion (see Figure 3.1) that are supergiants. Betelgeuse, which to a northern hemisphere observer is the bright star in the top left-hand corner of the constellation, is termed a red supergiant. The colour is perceptible, but is not very dramatic; as one's eyes become dark-adapted after 15 minutes or so, an orange tint becomes noticeable. A colour photograph taken with an ordinary camera will show it clearly. Rigel, at the opposite corner of the constellation, is a blue supergiant, shining with a blue-white light.

QUESTION 7.3

If a star moves from the upper main sequence in the top left-hand part of the H–R diagram to become a supergiant, what changes take place in its luminosity and surface temperature?

QUESTION 7.4

A main sequence star initially has a surface temperature of 25 000 K and radius $10R_\odot$. The temperature drops (without change of luminosity) to 5000 K as it becomes a (yellowish-white) supergiant. Use Equation 3.9 to determine its new radius. Express your answer in units of solar radius and AU.

As the result of Question 7.4 shows, supergiants may have very large radii. In fact, Betelguese has such a large diameter and is sufficiently close that it has been possible to resolve the stellar disc using the Hubble Space Telescope (Figure 3.17).

7.3.1 Massive stars on the main sequence

As with the less massive stars, the reason for a massive star moving off the main sequence is that a significant fraction of the hydrogen in the core has been consumed and converted into helium by nuclear fusion reactions.

- ■ What is the name of the set of nuclear fusion reactions that dominate in the heavier main sequence stars?
- ❑ The CNO cycle (Section 6.3.2).

QUESTION 7.5

Can you suggest a reason why there are so few stars in that part of the H–R diagram between the upper main sequence and the area where the supergiants lie?

The evolution of a massive star to a supergiant parallels the evolution of a less massive star to a red giant. In lower mass stars the pressure of the hot gas supports the star, whereas in more massive stars (over about $5M_\odot$) radiation pressure provides the dominant supporting force (Section 6.4.3).

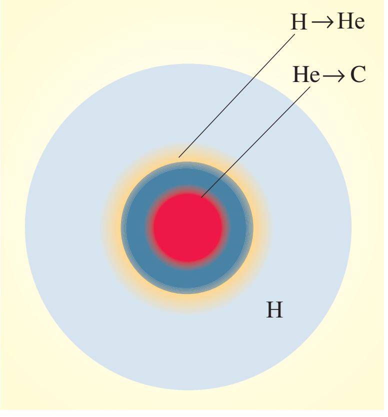

Figure 7.9 The structure of a helium-burning supergiant (not to scale).

7.3.2 After the main sequence

As you saw in Section 7.2.1, the nuclear burning slows as the fuel in the centre of the star is used up. Let's consider this process in a general sense. There is still burning where fresh material is available in a shell around the outer edge of the core, but the core is becoming choked with 'ash', i.e. nuclei that are the product of the nuclear reaction. As the nuclear reactions diminish, there is no longer the pressure gradient from the escaping radiation to balance the gravitational force and so the core contracts under gravity. A consequence of this contraction is that the density and the temperature of the core of the star rise, and there comes a point where what has been inert 'ash' can itself start to burn. Another nuclear fusion reaction can start, converting the material in the core into yet more massive nuclei, and once again producing energy. So the star keeps shining and again is in balance.

The first time this happens, after the main sequence, it is the fusion of helium to carbon (the 3α process, described in Section 7.2.2) that starts. While this phase lasts the star has two sources of energy from nuclear reactions (Figure 7.9): the fusion of helium to carbon in the core, and the fusion of hydrogen to helium in a shell outside the core.

By this stage the star has become a supergiant. Its surface temperature (and hence whether it is called blue, yellow or red) depends on the star's mass and the rate at which it loses mass through its stellar wind (see Section 7.3.5). Future changes in luminosity and temperature also depend on these properties. Some supergiants are always blue, some track from blue to red and stop there, and some will track back again from red to blue.

7.3.3 Astronomical alchemy

What happens next in the star, when the amount of helium available in the core for conversion into carbon diminishes noticeably? As the nuclear reaction wanes and the pressure gradient due to the escaping energy diminishes, the core of the star once again contracts under gravity. The core temperature goes up yet again and, at temperatures of about 3×10^8 K, the reaction

$$^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{16}_{8}\mathrm{O} + \gamma$$

can commence. The star then has three sources of energy from nuclear reactions.

- What are these three sources of energy?

- $^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{16}_{8}\mathrm{O} + \gamma$ in the core; the 3α process in a shell around the core; and hydrogen burning in a shell outside that again.

QUESTION 7.6

Sketch the structure of the star at this stage. (You might find it helpful to have Figure 7.9 in front of you as you do this.)

The supergiant star goes through this pattern of steps a number of times as successively heavier elements become scarce in the core. In contrast to lower mass stars, in stars initially over about $8M_{\odot}$, each new burning starts in a non-degenerate core. However, these later stages of evolution of a supergiant star are not fully understood, and what follows should be treated with caution; as our understanding continues to grow the details may well change. The following account describes the main phases of nuclear burning that a high-mass star is believed to experience, and highlights some of the more important nuclear reactions that are thought to take place in the core. In reality, many more nuclear reactions take place than can be described here.

When helium burning stops, the carbon and oxygen core of the star contracts and at a temperature of about 5×10^8 K **carbon burning** commences. The fusion of two nuclei can have different outcomes. The simplest outcome, which actually occurs rather infrequently, is the formation of magnesium:

$$^{12}_{6}\mathrm{C} + {}^{12}_{6}\mathrm{C} \rightarrow {}^{24}_{12}\mathrm{Mg} + \gamma$$

The two most likely reactions are those that produce sodium and neon:

$$^{12}_{6}\mathrm{C} + {}^{12}_{6}\mathrm{C} \rightarrow {}^{23}_{11}\mathrm{Na} + {}^{1}_{1}\mathrm{H}$$

$$^{12}_{6}\mathrm{C} + {}^{12}_{6}\mathrm{C} \rightarrow {}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He}$$

The reaction that produces sodium also results in the emission of a proton ($^{1}_{1}\mathrm{H}$), while that which forms neon also forms an α-particle. Thus, very light nuclei tend to be formed as by-products.

QUESTION 7.7

What would happen to a proton or an α-particle in this environment? Suggest a reaction that has already been described that might occur. Is it likely that a significant amount of hydrogen or helium would build up in the core as a result of carbon burning?

The effect of carbon burning is to create elements with mass numbers (A) of around 20 and to produce protons and helium nuclei which undergo fusion reactions with any of the heavier elements (from carbon to magnesium) that are present in the core.

As carbon becomes depleted, the core contracts and heats up, and at a temperature of about 10^9 K a new type of process starts to become important. As an introduction to this process it is useful to consider the following question.

QUESTION 7.8

Calculate the wavelength of the peak of the black-body spectrum corresponding to a temperature of 10^9 K. In what part of the electromagnetic spectrum does this peak lie?

As Question 7.8 revealed, the core is so hot that the black-body spectrum extends into the γ-ray part of the spectrum. This is significant because many fusion reactions that release energy in the form of a γ-ray can be reversed. For example, a reaction that occurs at temperatures of about 3×10^8 K (i.e. before the onset of carbon burning) is the formation of neon by the reaction

$${}^{16}_{8}\text{O} + {}^{4}_{2}\text{He} \rightarrow {}^{20}_{10}\text{Ne} + \gamma$$

However, this reaction can be reversed if nuclei of ${}^{20}_{10}\text{Ne}$ are in an environment where there are γ-rays:

$${}^{20}_{10}\text{Ne} + \gamma \rightarrow {}^{16}_{8}\text{O} + {}^{4}_{2}\text{He}$$

Since the effect is that of a nucleus being split up by a γ-ray photon, this process is called **photodisintegration**. At the core temperatures that occur after carbon burning, this photodisintegration reaction plays an important role in the next stage of nuclear burning.

■ What does the core of the star consist of at the end of carbon burning?

❑ From the carbon burning reactions, the core will consist of neon, sodium and (some) magnesium.

At temperatures greater than 1.5×10^9 K some of the neon will undergo photodisintegration to oxygen according to the reaction described above. The other product of this reaction is α-particles, which can react with nuclei of ${}^{20}_{10}\text{Ne}$ (that have not undergone photodisintegration) to form magnesium:

$${}^{20}_{10}\text{Ne} + {}^{4}_{2}\text{He} \rightarrow {}^{24}_{12}\text{Mg} + \gamma$$

These processes have the effect of changing the composition of the core to being a mixture of oxygen and magnesium. This stage is sometimes referred to as **neon burning** although it should be noted that the reaction is not a simple fusion reaction between two nuclei of neon.

After neon burning, the core yet again contracts and the temperature rises. At about 2×10^9 K the oxygen nuclei start to react to form silicon by a process called **oxygen burning**:

$${}^{16}_{8}\text{O} + {}^{16}_{8}\text{O} \rightarrow {}^{28}_{14}\text{Si} + {}^{4}_{2}\text{He}$$

As in the carbon and neon burning phases, the α-particles formed in this reaction quickly disappear as they take part in fusion reactions with heavier nuclei.

Once the oxygen in the core is exhausted, the core contracts yet further and the temperature reaches about 3×10^9 K. At this temperature, the photodisintegration of silicon starts:

$${}^{28}_{14}\text{Si} + \gamma \rightarrow {}^{24}_{12}\text{Mg} + {}^{4}_{2}\text{He}$$

As was earlier the case with the photodisintegration of neon, this provides a source of α-particles. These α-particles rapidly undergo fusion reactions with silicon and with the subsequent products of fusion, leading to sequences of reactions such as:

$${}^{28}_{14}\text{Si} + {}^{4}_{2}\text{He} \rightarrow {}^{32}_{16}\text{S} + \gamma$$

$$^{32}_{16}\mathrm{S} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{36}_{18}\mathrm{Ar} + \gamma$$

$$^{36}_{18}\mathrm{Ar} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{40}_{20}\mathrm{Ca} + \gamma$$

This type of reaction will proceed as far as producing elements with atomic masses up to $A \sim 56$, such as iron, chromium, manganese, cobalt and nickel (these are termed the **iron group** elements). As we will see below, this is the limit of nuclear burning. This phase of the star's life is often called **silicon burning**.

While the photodisintegration that occurs during silicon burning absorbs energy, the nuclear reactions that form nuclei up to the iron group will produce somewhat more energy. The overall effect is a net release of energy and the conversion of most of the silicon core into iron. When this process is complete, the core temperature is about 7×10^9 K. Surrounding this core, like the layers in an onion, are shells consisting mainly of Si and S, O and C, He, and H, as shown in Figure 7.10.

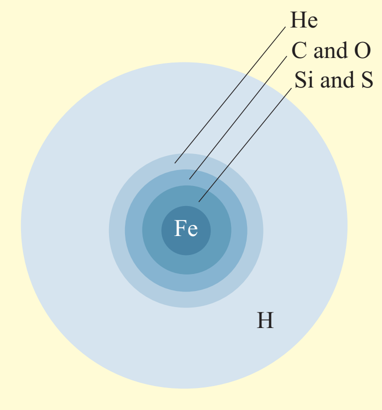

Figure 7.10 The structure of a highly evolved supergiant (not to scale) on the last day of its life.

QUESTION 7.9

In each of the stages of a supergiant's life cycle the conversion of hydrogen into helium has been taking place somewhere in the star. Describe how the site of this reaction moves as the star evolves.

7.3.4 Diminishing returns

We shall next see that each new reaction is less efficient than the previous at releasing energy, so reactions have to go faster (i.e. the number of nuclei that undergo reactions every second has to increase) to produce the necessary radiation to balance gravity. The faster reaction rates in the later stages of the star's life also mean there are more neutrinos produced, and these carry away a growing proportion of the energy generated. Nearly all the neutrinos escape without interacting with the outer layers of the star (Section 2.2.4) so do not contribute to its pressure balance. So the star goes through its life cycle at an ever-increasing pace, squandering its reserves faster and faster.

This is reflected in the fact that the time spent in each core nuclear burning phase gets dramatically shorter as the burning progresses to heavier elements. We saw in Section 7.2.2 that the time that a star spends in the core helium burning phase of its life is about 10% of the time that the star spends on the main sequence. For example, in a $25M_\odot$ star the hydrogen and helium burning phases are approximately 7×10^6 years and 5×10^5 years respectively. For this star the carbon burning phase is likely to last about 600 years, the neon burning and oxygen burning phases last for about a year and for about six months respectively. The final stage, that of silicon burning is estimated to last only about a day!

Broadly speaking, as the star progresses to the fusion of more massive elements, the energy released per kilogram of material undergoing the reaction diminishes. The full proof of this statement is beyond the scope of this book, but one can sense the correctness of it by looking at the left-hand side of Figure 6.6, plotted here as Figure 7.11.

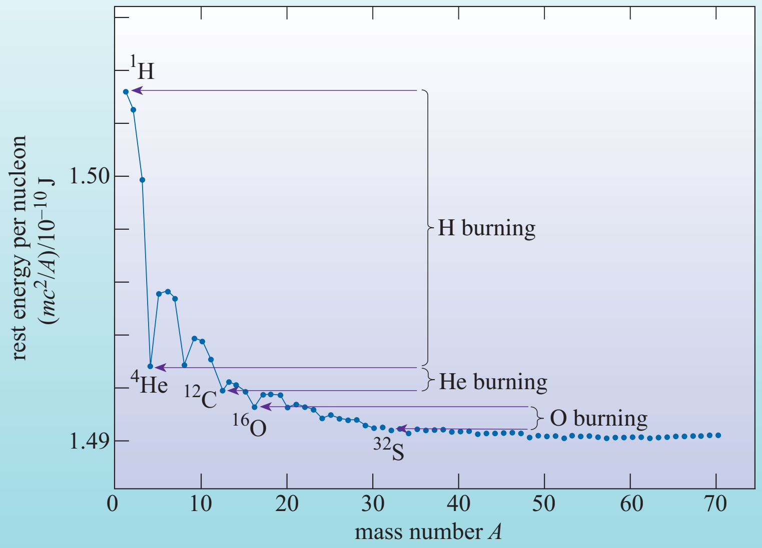

Figure 7.11 The variation of rest energy per nucleon with mass number, up to $A = 70$. As the mass of the nucleons undergoing fusion in a star increases, the available energy decreases.

You learnt in Chapter 6 that the fusion of light elements is exothermic, i.e. energy is released. Energy is released by a reaction if the product is at a lower value of rest energy per nucleon than the reactant(s). However, the curve in Figure 7.11 is gradually flattening – its gradient is becoming shallower – so the energy produced by a fusion reaction decreases with mass, as indicated by the examples shown.

- What do you suppose will happen when the fusion reactions have built up to the element iron ($A = 56$), which is where the curve in Figure 6.6 has its minimum?

- In some sense, yet to be spelled out, the star has reached the end of the road. Any change in nuclear composition would consume rather than produce energy, whether fusion to an element of higher A or fission to an element of lower A.

We will investigate what happens next in Chapter 8.

7.3.5 The most massive stars

The evolution of stars of very high mass (i.e. over $50M_\odot$) occurs extremely rapidly. Their evolution is also dramatically affected by mass loss (remember that radiation pressure rather than gas pressure is the dominant force opposing gravity for such stars). Whereas main sequence stars like the Sun lose mass through their stellar winds at rates of $10^{-14}M_\odot$ year^{-1}, massive O-type stars lose mass through their stellar winds at a rate of up to $10^{-6}M_\odot$ year^{-1}.

QUESTION 7.10

Calculate and compare the fraction of the mass lost by a star of solar mass and one of $50M_\odot$ during their main sequence lifetimes (10^{10} years and 10^6 years respectively).

Your answer to Question 7.10 shows that the total mass loss during the main sequence phase, as a fraction of the mass of the star, increases as the star's mass increases, despite the very much shorter lifetime.

The most massive stars of around $100M_{\odot}$ may lose up to half their mass before the end of their main sequence lifetime. The outer layers of these stars are lost and the core is exposed so that the products of nucleosynthesis (in this case the CNO cycle), are revealed. Their spectra therefore imply a much greater abundance of helium near the surface than most stars. In addition, their evolution is drastically changed since they will not be able to undergo shell burning (there is no longer any region above the core for it to occur) and never become red supergiants. These objects are known as **Wolf–Rayet stars** after their discoverers (C. S. E. Wolf and G. Rayet). The expanding shells of gas around the stars as a result of their mass loss may be observable directly, as in Figure 7.12, or be inferred from the structure of the emission lines seen in their spectra (see Figure 7.13).

The final stages of the evolution of high-mass stars, which involves variability, significant mass loss and a catastrophic finale in a supernova, are described in Chapter 8.

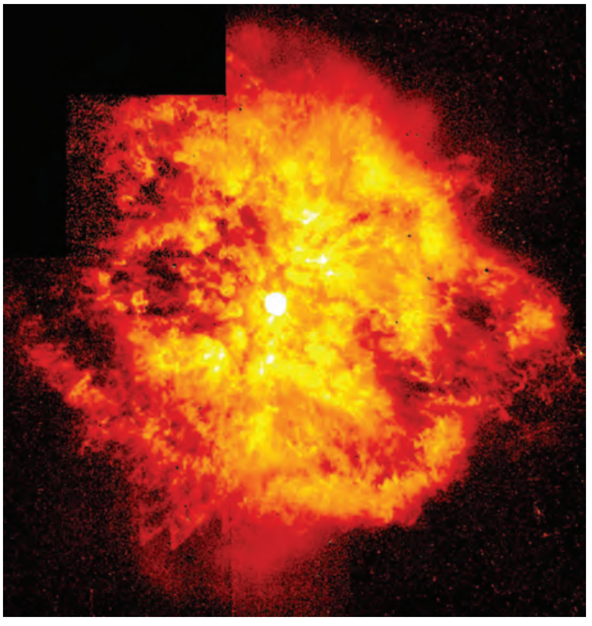

Figure 7.12 The Wolf–Rayet WR124 surrounded by gas ejected during the last 10 000 years. (Y. Grosdidier (University of Montreal and Observatoire de Strasbourg), A. Moffat (University of Montreal), G. Joncas (Université Laval), A. Acker (Observatoire de Strasbourg)/NASA)

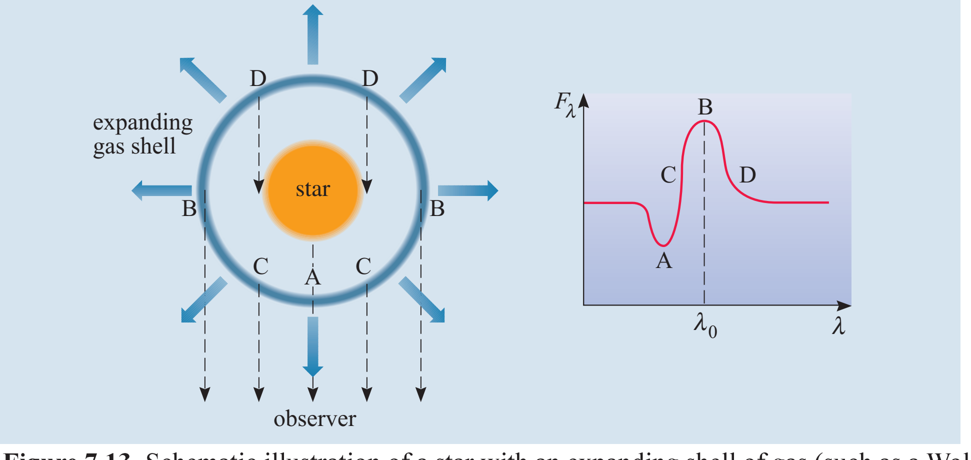

Figure 7.13 Schematic illustration of a star with an expanding shell of gas (such as a Wolf–Rayet star) showing how the characteristic spectral lines are produced. Material at position C has a component of motion towards the observer so emission lines from this glowing gas are blue-shifted relative to those emitted by gas in region B, which is moving perpendicular to the line of sight (and therefore has no Doppler shift relative to the star, which defines the wavelength λ_0). Similarly, light from region D is moving away from the observer and is red-shifted relative to B. In region A, the maximum blue-shift occurs but an absorption line is seen because some of the radiation from the hotter star behind is absorbed and re-emitted in other directions.

7.4 Summary of Chapter 7

Low-mass stars

- The main sequence lifetime of a star ends when the hydrogen in the core is exhausted.
- The core contracts and the temperature rises sufficiently for hydrogen shell burning to start in a region surrounding the helium core.
- At a temperature of around 10^8 K, helium burning is initiated. This is the 3α process. In stars of mass less than $2.25M_\odot$, the electrons in the core first become degenerate. This leads to a core helium flash.
- This transition phase is accompanied by a contraction and heating of the core but a swelling of the diameter by typically a factor of 10, and a cooling of the surface. The star becomes a red giant.
- For stars of mass less than $0.5M_\odot$, the temperature in the core does not rise high enough for helium burning to start.
- After depletion of helium in the core, helium burning continues in a shell surrounding the core, accompanied by periodic shell helium flashes. This shell helium burning causes a further swelling of the red giant.
- These changes in energy source and structure cause the star to move on the H–R diagram from the main sequence to the red giant branch (RGB), horizontal branch (HB) and asymptotic giant branch (AGB).
- During their helium core burning stage the conditions in the envelopes of stars lead to an instability and they undergo pulsations. This occurs in a region of the H–R diagram called the instability strip. Stars of mass above $2M_\odot$ become Cepheid variables.
- The giant phase lasts for approximately 10% of the main sequence lifetime.
- In giants, fusion reactions can also produce oxygen and neon. The capture of neutrons (s-process) produces heavier elements.
- Red giants suffer more significant mass loss due to stellar winds than they did when they were main sequence stars.

High-mass stars

- Massive stars spend less time on the main sequence than less massive stars, and then evolve across the H–R diagram more quickly.
- When a significant fraction of the hydrogen in the core of a massive star has been converted into helium, the star moves off the main sequence to become a supergiant.
- In stars of initial mass greater than about $8M_\odot$, carbon burning (to produce magnesium, sodium and neon) is followed by a range of reactions dependent on mass which can result in the formation of nuclei as massive as iron.
- These reactions may be fusion of identical nuclei (e.g. in oxygen burning to produce silicon), photodisintegration of a nucleus by a γ-ray photon to produce a lighter nucleus (e.g. the production of magnesium from silicon), or fusion with a helium nucleus (e.g. production of sulfur from silicon).
- Each new reaction produces energy less efficiently than the previous one; to compensate, the reaction rate is greater.
- The most massive stars lose mass at a prodigious rate through stellar winds, which drastically changes their evolution. Wolf–Rayet stars lose their entire outer layers to expose the core.

Questions

QUESTION 7.11

Sketch an H–R diagram and on it mark the area occupied by the supergiants, identifying the positions of red, yellow and blue supergiants. Show the evolutionary tracks of supergiants that evolve from blue to red, and of supergiants that change from blue to red and back again. Show from what part of the main sequence the supergiants have come.

QUESTION 7.12

For a $25M_{\odot}$ star; (a) arrange the following stages of core nuclear burning in chronological order of occurrence: silicon burning, neon burning, helium burning, carbon burning, hydrogen burning, oxygen burning. (b) State which of these stages involve fusion of two (or more) identical nuclei, and those in which photodisintegration plays an important role. Briefly explain in words what the effect of photodisintegration is.

QUESTION 7.13

Explain in your own words why a massive star goes through its life cycle at an ever-increasing pace.